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The Use of Colloidal Carbon in Grinding Clinker.

EXPERIMENTS which show that the addition of small proportions of colloidal carbon effects considerable improvements in clinker grinding have been made by Mr. C. W. Sweitzer and Mr. A. E. Craig at the Mellon Institute of Industrial Research, Pittsburgh. The experiments and the results obtained are reported in *Industrial and Engineering Chemistry* (June, 1940), from which journal the following abstract is taken.

The colloidal state of subdivision of colloidal carbon, coupled with its chemical inertness, led to its proposal as a likely grinding aid. This paper presents the findings in a study on the utility of colloidal carbon, commonly known as carbon black, as a grinding aid in the manufacture of Portland cement. The results of numerous physical tests made on cements are included.

Experimental Procedure.

The colloidal carbon used throughout this study was the grade termed "Cem Beads," a pellet form of a standard channel carbon manufactured from natural gas, with physical and chemical properties essentially similar to the colloidal carbon pigment used in the rubber industry. The diameter of the ultimate carbon particles in the pellet averages about 60 millimicrons (0·000002 inch) and thus indicates the colloidal nature of the pigment.

Since no one Portland cement clinker could be classed as typical for the whole United States, four representative clinkers were studied, namely, A, an eastern type reputedly hard to grind; B, an eastern type reputedly normal grinding; C, a mid-western type reputedly easy to grind; D, a southern type reputedly hard to grind.

The standardised grinding technique embraced the following: Mill: No. 9, 18 in. by 18 in., all-steel welded construction, Abbé ball mill, 42·8 revolutions per

minute. Ballast Charge: 100 lb. of 0·75-in. forged steel balls. Clinker Charge: 15 lb., crushed and conditioned as follows: 10 lb. through No. 14 sieve retained on No. 100 sieve, 5 lb. through No. 100 sieve. Gypsum Charge: 210 to 220 grams (0·463 to 0·484 lb.), depending on the clinker. Carbon Charge: Varied. Grinding Time: 60 minutes in constant grinding time experiments; variable in constant fineness experiments. Precautions: The usual cleaning precautions which included scouring between experimental grinds.

TABLE I.—EFFECT OF COLLOIDAL CARBON ON FINENESS AND OTHER PROPERTIES OF CEMENTS.

	% Carbon by Weight on Clinker									
	0	0.02	0.04	0.08	0.16	0.32	0.64	1.28	2.56	5.12
Clinker A										
Sp. surface, sq. cm./gram	1170	1200	1260	1370	1520	1590	1680	1750	1740	1740
Sieve analysis										
% through 200 mesh	87.4	88.1	90.7	91.6	93.7	95.1	95.1	95.4	95.2	94.9
% through 325 mesh	75.4	75.4	78.5	81.2	84.6	89.2	89.2	92.3	91.0	89.9
Normal consistency, cc.	24.0	24.0	24.0	24.5	24.5	25.5	27.5	28.5	29.5	32.5
Water-cement ratio	0.61	0.61	0.61	0.61	0.62	0.62	0.62	0.63	0.63	0.65
Setting time, hr.: min.										
Initial	4:40	4:40	4:30	4:00	3:30	3:00	2:15	2:00	2:30	4:20
Final	6:40	6:40	6:20	6:00	5:40	5:15	5:00	4:20	5:15	6:10
Soundness	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Clinker B										
Sp. surface, sq. cm./gram	1250	1290	1330	1350	1530	1650	1800	2040	1900	1910
Sieve analysis										
% through 200 mesh	90.0	90.7	91.4	92.3	93.4	94.8	95.1	95.8	94.6	95.3
% through 325 mesh	78.5	80.4	81.7	82.1	83.8	89.9	92.0	95.3	92.2	92.7
Normal consistency, cc.	22.5	22.5	22.5	22.5	24.5	25.0	26.0	28.5	29.0	31.5
Water-cement ratio	0.57	0.57	0.57	0.57	0.58	0.58	0.59	0.59	0.59	0.61
Setting time, hr.: min.										
Initial	3:00	3:00	3:00	3:25	3:20	2:20	2:15	3:30	4:10	4:30
Final	6:00	6:00	5:50	5:40	6:10	5:30	5:35	5:45	7:20	8:00
Soundness	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Clinker C										
Sp. surface, sq. cm./gram	1220	1230	1250	1330	1500	1620	1800	1930	2090	2230
Sieve analysis										
% through 200 mesh	90.8	89.4	89.9	91.4	93.8	94.8	95.0	95.7	95.2	95.5
% through 325 mesh	79.0	77.8	78.7	80.5	83.6	89.6	91.1	93.1	91.5	93.0
Normal consistency, cc.	21.5	21.0	21.5	22.5	23.0	25.0	25.5	26.5	28.5	31.5
Water-cement ratio	0.56	0.56	0.56	0.56	0.57	0.57	0.57	0.58	0.58	0.60
Setting time, hr.: min.										
Initial	3:30	3:30	3:25	3:20	3:20	3:00	2:50	3:35	3:30	4:15
Final	6:40	6:45	6:30	6:20	6:10	5:45	5:40	6:50	7:15	7:45
Soundness	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Clinker D										
Sp. surface, sq. cm./gram	1430	1440	1410	1460	1520	1680	1770	1820	1900	1850
Sieve analysis										
% through 200 mesh	91.5	91.0	91.4	93.1	95.0	95.8	97.1	97.6	97.6	96.8
% through 325 mesh	76.2	76.2	75.3	77.4	79.1	81.4	84.0	83.9	88.6	83.6
Normal consistency, cc.	22.0	22.0	22.0	22.0	22.5	23.0	25.0	25.0	28.5	31.0
Water-cement ratio	0.57	0.57	0.57	0.57	0.58	0.58	0.59	0.60	0.61	0.63
Setting time, hr.: min.										
Initial	3:40	3:45	3:30	3:30	3:10	3:30	4:00	4:15	4:15	4:45
Final	6:30	6:40	6:30	6:20	6:00	6:00	6:30	6:45	7:00	8:10
Soundness	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

The mill speed was calculated to lie just within the range considered as good practice. The ballast charge was restricted to 0·75-in. balls because of structural limitations in the mill. A higher mill speed together with a graded ball charge would improve the grinding efficiency of the mill and raise the fineness values recorded in *Table* I. However, since the primary purpose of this study was to determine fineness differences, it was not deemed necessary to make major alterations on the mill in order to secure higher values.

The quantities of carbon used (per cent. by weight of clinker) were 0·02, 0·04, 0·08, 0·16, 0·32, 0·64, 1·28, 2·56, and 5·12. This range was selected in the expectation that it would include the optimum proportion.

Standard or tentative A.S.T.M. methods were used in the following tests: specific surface, sieve analysis, soundness, setting time, normal consistency, tensile strength, and compressive strength. Approved methods were followed in the freezing and thawing and the sulphate resistance tests.

The bulk of the experimental work was carried out under the condition of constant grinding time. The procedure followed was to complete all grinds and subsequent tests on one clinker before studying the next. Some experimental work was also carried out under the condition of grinding to constant fineness. Other studies included evaluation of the resistance of experimental cements to freezing and thawing and to immersion in sulphate solution.

Physical Properties of Cements.

The physical test data, including fineness, on the experimental cements prepared with the use of colloidal carbon at a constant grinding time of 60 minutes are given in *Table* I.

FINENESS BY TURBIDIMETER AND SIEVE ANALYSIS.—The specific surface values in *Table* I were determined by the Wagner turbidimeter according to the tentative A.S.T.M. method C115–38T. The 200-mesh sieve analysis results were obtained according to the standard A.S.T.M. method C77–37. The 325-mesh sieve analysis was according to Wagner as described in the tentative A.S.T.M. method C115–38T.

Inspection of the sieve analysis results in *Table* I reveals that, in general, the effect of colloidal carbon is gradually to increase the fineness of the cements to a maximum value which is reached roughly with the addition of 1 per cent. of colloidal carbon. The effect of additions beyond 1 per cent. appears gradually to decrease the fineness values. The effect of the carbon is undoubtedly positive at its lowest percentage (0·02), but the increase does not become distinctly greater than the possible experimental error until the amount of carbon reaches 0·04 per cent. The trend in fineness values shown by the sieve analysis is confirmed by the specific surface results, with the exception that the latter display a tendency to plateau or slightly increasing values for cements with quantities of carbon above 1 per cent. This result is ascribed to the effect of colloidal carbon in increasing the specific surface measurements, as determined by the Wagner turbidimeter, by decreasing the microampere readings due to increased opacity. Tests showed that this effect of the colloidal carbon is negligible for additions below 1 per cent. but becomes measurable for higher percentages. Undoubtedly the application of such a correction factor to the recorded values for cements containing 2·56 and 5·12 per cent. carbon would reduce these values to figures below those shown for 1·28 per cent. carbon, and thereby bring the specific surface results more in conformity with the trend established by the 325-sieve analysis. However, such corrections were not applied to the results given in *Table* I because of the difficulty in determining accurately the true correction factor.

The sieve analysis and specific surface results for the four clinkers recorded

in *Table I* were averaged, and the composite values are plotted in *Fig.* 1. The sieve analysis graphs demonstrate a gradually increasing fineness for the cements with increasing additions of carbon, to a maximum value which is reached roughly in the neighbourhood of 1 per cent. With this proportion the specific surface graph reaches essentially plateau values. Based on the discussion of specific surface results in the previous paragraph, it would seem reasonable to accept the first value on this pleateau range (i.e., for 1·28 per cent. carbon) as a measure of the maximum increase of fineness according to specific surface measurements. Taking this figure, rather than the slightly greater values given with the larger proportions of carbon, the maximum specific surface increase over control approximates 50 per cent.

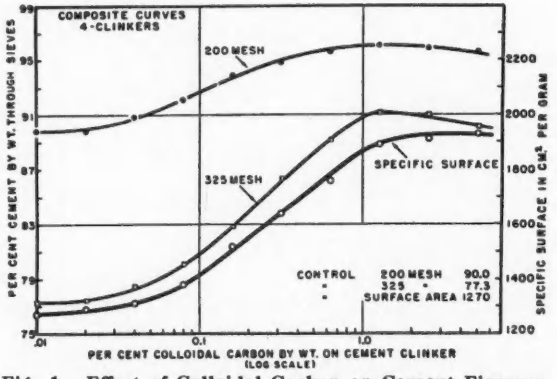

Fig. 1.—Effect of Colloidal Carbon on Cement Fineness.

The cement containing 1·28 per cent. of colloidal carbon is dark in colour and for this reason may prove undesirable in use. The cements containing 0·16 and 0·32 per cent. of carbon are not much darkened, but show striking increases in fineness as indicated by the following values interpolated from the specific surface graph in *Fig.* 1.

Per cent. Carbon	Specific Surface, sq. cm. per gram	Per cent. Increase over control
Control	1,270	0
0·16	1,510	19
0·32	1,640	30
0·64	1,780	40
1·28	1,890	49

The control specific surface values in *Table* I are lower than those of normal commercial Portland cements. These lower values are due to the laboratory grinding described, which was found satisfactory for the comparative tests of this study although it gave lower fineness results than cements ground by commercial methods.

WATER REQUIREMENTS OF CEMENTS.—All the mortars used in the preparation of strength test specimens were of constant consistency. This necessitated the determination of the water requirements, for the different experimental cements, needed to give constant consistency. In the preparation of tensile briquette specimens from standard 1 : 3 mortars according to A.S.T.M. method C77–37, the water requirements for constant consistency were determined by the normal consistency test on neat cement pastes according to method C77–37. These values are recorded in *Table* I as normal consistency. In the preparation of compression cube specimens from standard 1 : 2·75 mortars according to A.S.T.M. method C109–37T, the water requirements for constant consistency were determined according to the procedure used in A.S.T.M. method C91–38T. These values are recorded in *Table* I as water-cement ratio.

The results in *Table* I bring out that the effect of colloidal carbon is to increase the water requirement of the cement as shown by both the normal consistency and the water-cement ratio results. This increase is attributed largely to the increased fineness of the cement resulting from the use of colloidal carbon, but also partly to the absorption of water by the carbon itself. The relative effects of increased fineness and of absorption by carbon on these values can be roughly determined from the results.

The increase in water requirement from the 2·56 to the 5·12 per cent. carbon-containing cements can be assumed to be caused by the carbon because no increase appears in the cement fineness by either the sieve analysis or the specific surface measurements (clinker C excepted). From the normal consistency values for these high percentages, a calculation shows that 1 per cent. of colloidal carbon increases the amount of water required by about 1 cc. Therefore, in the case of the 1·28 per cent. carbon-containing cement, 75 per cent. of the increase in normal consistency would seem to be due to increased fineness and the remaining 25 per cent. to the carbon content.

TIME OF SETTING.—The setting-time values in *Table* I were determined for all the experimental cements by the Gillmore method as described in A.S.T.M. C77–37. The results reveal that the setting time decreases with increasing fineness of the cement but increases with increasing quantities of carbon if the fineness of the cement remains constant. In quantities below 1 per cent., however, the effect of the carbon in increasing setting time would appear to be negligible.

SOUNDNESS.—Tests were made on all the experimental cements by the standard steaming method as described in A.S.T.M. method C77–37. The results in *Table* I show that colloidal carbon, at all the percentages used, with all four clinkers studied, had no adverse effect on soundness. These tests were repeated on all experimental cement samples after three-months' storage, and the results were the same.

Strength of Mortars.

Results of all strength tests on mortars are recorded in *Table* II. All values are averages of six readings, weighting the results following the method specified by the A.S.T.M. The cements used in these tests had the fineness and water-requirement properties indicated in *Table* I.

TENSILE STRENGTH.—The tensile strength results given in *Table* II were determined on mortar briquettes prepared, cured, and tested according to the standard A.S.T.M. method C77–37. The proportions were 1 part cement to 3 parts standard Ottawa sand. Since the cements showed varying fineness values, the mortar specimens were prepared with the corresponding water-requirement ratios as determined by the normal consistency values given in *Table* I. All the specimens were broken on an Amsler hydraulic testing machine. Although the

TABLE II.—EFFECT OF COLLOIDAL CARBON ON THE STRENGTH OF CEMENT.

		% Carbon by Weight on Clinker								
		0	0.02	0.04	0.08	0.16	0.32	0.64	1.28	2.56	5.12
Clinker A											
Tensile strength	1 day	120	151	152	139	187	165	139	168	162	113
	3 days	252	224	271	305	289	291	265	329	305	227
	7 days	314	340	357	365	347	366	355	361	331	312
	28 days	403	397	412	436	403	419	371	382	416	366
Compressive strength	1 day	224	362	271	188	349	216	221	291	251	213
	3 days	1030	1154	1137	1054	1612	1526	1175	1571	1183	1066
	7 days	1900	2150	2116	1891	2283	2400	2720	2741	2383	2166
	28 days	3141	3533	3595	3400	3966	2841	4105	3941	3595	3486
Clinker B											
Tensile strength	1 day	118	134	110	105	103	105	133	93	173	73
	3 days	248	254	261	266	221	208	241	190	231	205
	7 days	330	333	323	318	285	290	287	296	286	280
	28 days	380	385	350	357	360	350	303	323	278	263
Compressive strength	1 day	195	157	166	186	162	146	137	160	136	104
	3 days	871	908	958	1012	1141	1050	1082	1130	995	824
	7 days	1716	1891	1979	2166	2237	2492	2579	2550	2004	1892
	28 days	3229	3448	3641	4058	3508	3925	3533	3600	3375	2775
Clinker C											
Tensile strength	1 day	94	96	108	120	128	135	130	140	130	120
	3 days	218	210	220	220	235	245	250	240	235	228
	7 days	288	300	323	365	330	340	360	343	310	296
	28 days	370	376	375	397	424	426	365	420	410	355
Compressive strength	1 day	279	313	337	216	250	275	290	400	500	323
	3 days	1229	1118	1216	1216	1491	1516	1391	1216	1860	1160
	7 days	2041	1942	1912	2175	2616	2650	2608	2633	2660	1776
	28 days	3375	3375	3791	4116	4087	4258	3650	4491	4283	3108
Clinker D											
Tensile strength	1 day	104	81	89	116	115	100	115	116	88	60
	3 days	206	235	202	237	249	216	220	215	215	180
	7 days	315	314	310	320	320	290	298	315	305	288
	28 days	367	395	394	395	405	412	395	412	385	360
Compressive strength	1 day	250	187	262	325	375	262	270	279	133	125
	3 days	883	1008	979	1171	1312	1023	1225	1383	1091	800
	7 days	1933	1942	1950	2258	2377	2220	2129	2575	2141	2005
	28 days	3314	3200	3412	3660	3694	3816	3622	3950	3554	3016
	60 days	3680	3805	3790	3685	4000	3825	4155	4258	4012	3220
	90 days	4292	4275	4258	4066	4475	4340	4725	4925	3658	3458

[a] All values are in pounds per square inch; to convert to kilograms per square centimeter, multiply by 0.07.

general trend of these results is self-evident, attention is drawn to certain irregularities in the data. They are ascribed partly to the rather abrupt changes in the water content of the test specimens (*Table* I gives normal consistency values) and partly to occasional difficulties with the testing machine. Thus, as an example of the effect of changes in water content, the lower 28-day readings for the cements containing 0·64 per cent. carbon coincide with an increase in water content as indicated by the normal consistency values for these cements.

The results in *Table* II demonstrate a general tendency to higher tensile

strengths for the cements containing colloidal carbon. This tendency is apparent in all the tests from 1 to 28 days. *Fig.* 2 is a composite graph of the 28-day tests, averaging the results for four clinkers. It shows increasing tensile strength with increasing proportions of carbon to a maximum value of about 0·5 per cent. Higher quantities of carbon reduce the strength gradually, but increases over the control are shown up to 2 per cent. At the maximum point the increase in strength is approximately 6 per cent. over the control.

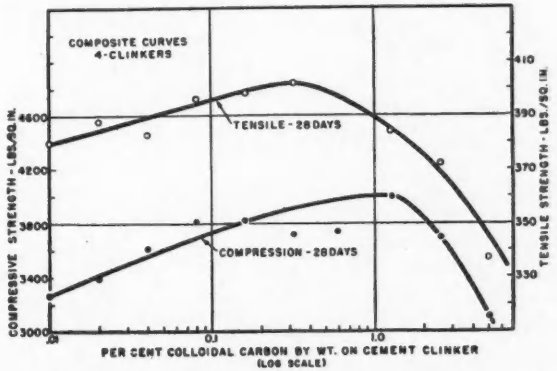

Fig. 2.—Effect of Colloidal Carbon on the Strength of Cements.

A composite strength improvement value, in terms of percentage of control, can be calculated from all the results, for cements containing 0·02 to 1·28 per cent. of carbon :

PERCENTAGE CHANGE IN TENSILE STRENGTH FOR CEMENTS CONTAINING FROM 0·02 TO 1·28 PER CENT. COLLOIDAL CARBON

Time, days	Test A	Test B	Test C	Test D
1	+31	−6	+30	0
3	+ 6	−5	+ 6	+9
7	+13	−8	+17	−9
28	0	−9	+ 8	+2

Average of all tests, +6·2 per cent.

From these results the improvement in tensile strength for all cements containing carbon (up to and including 1·28 per cent.) can be expressed as a single index number, + 6·2 per cent. A similar calculation for the cements containing only 1·28 per cent. of carbon gives a tensile strength increase of 8·4 per cent. The increased strengths are greatest for the shorter tests and least for the 28-day tests, which indicates the earlier hardening of cements containing carbon.

The results in these tests are undoubtedly influenced by three factors—cement fineness, water ratio, and proportion of carbon. The effect of increased water

in the preparation of mortars is to decrease strength; the effect of increased cement fineness is to increase strength. From the fact that the net trend of the results is positive for all cements containing up to 1·28 per cent. of colloidal carbon, it seems safe to conclude that colloidal carbon does not in any way decrease the tensile strength of the cement; in fact, on the evidence of these tests, it has a moderately beneficial effect.

COMPRESSIVE STRENGTH.—The compressive strength results given in *Table* II were determined on mortar cubes prepared, cured, and tested according to the tentative A.S.T.M. method C109–37T. The proportions of the mortar were 1 part cement to 2·75 parts graded Ottawa sand. As the cements showed varying fineness values, the mortar specimens were prepared with the corresponding water-requirement ratios as determined by the water-cement ratio values given in *Table* I. All the specimens were broken on an Amsler hydraulic testing machine. No satisfactory explanation can be offered for the generally lower results with clinker B cements, particularly for the 1-day tests. These cements possessed fineness values equal to the others (*Table* I) and otherwise behaved normally.

The results in *Table* II demonstrate a decided tendency to higher compressive strengths for the cements containing colloidal carbon. This tendency is apparent in all the tests from 1 to 90 days. A composite graph of the 28-day tests, averaging the results for four clinkers, is shown in *Fig.* 2. The graph reveals increasing compressive strength with increasing quantities of carbon in the cement, to a maximum value at about 1·0 per cent. Higher percentages of carbon reduce the strength gradually, but increases over the control are shown up to 4 per cent. At the maximum point the increase is approximately 23 per cent.

A composite strength improvement value, in terms of percentage of control, can be calculated from all the results, for cements containing 0·02 to 1·28 per cent. of carbon:

PERCENTAGE CHANGE IN COMPRESSIVE STRENGTH FOR CEMENTS CONTAINING FROM 0·02 TO 1·28 PER CENT. CARBON

Time, days	Test A	Test B	Test C	Test D
1	+21	−19	+ 7	+12
3	+28	+20	+ 7	+31
7	+23	+32	+16	+14
28	+15	+13	+17	+ 9
60	—	—	—	+ 7
90	—	—	—	+ 3

Average of all tests, +14

From these results the improvement in compressive strength for all cements containing carbon (up to and including 1·28 per cent.) can be expressed as a single index number, + 14 per cent. This index value for all cements containing from 0·08 to 1·28 per cent. of carbon, inclusive, becomes 23 per cent. For all cements containing 1·28 per cent. of carbon, this improvement index value is 26 per cent.

TABLE III.—FREEZING AND THAWING TESTS IN TAP WATER.

Properties of Cements[a]				Properties of Mortars[b]										
					% Loss in weight[c] after cycles:									
Group No.	% carbon by wt.	Fineness (325 mesh)	Water-cement ratio	Days cured	20	30	40	50	66	80	100	120	140	160
1	0	76.2	0.57	7	..	....	..	Discontinued at 50 cycles						
2	0.32	81.4	0.58	7	..	....	..	Discontinued at 50 cycles						
3	1.28	83.9	0.60	7	..	....	..	100						
4	0	89.9	0.66	7	..	100 (at 22 cycles)								
5	0.32	90.2	0.66	7	..	100 (at 25)								
6	0	89.9	0.66	28	..	....	..	100 (at 55)						
7	0.32	90.2	0.66	28	..	....	..	100 (at 55)						
8	0	80.4	0.59	60	..	....	..	3.4	6.0	17	30	41	100 (at 129)	
9	0	85.1	0.60	60	..	....	..	2.2	4.9	20	34	100 (at 118)		
10	0	94.4	0.61	60	..	....	..	3.2	8.3	26	100 (at 92)			
11	0.16	88.1	0.60	60	..	....	..	1.8	3.4	11	27	40	57	100 (at 153)
12	0.64	87.9	0.60	60	..	....	..	2.2	2.6	10	27	41	57	100 (at 153)
13	1.28	87.1	0.60	60	..	....	..	1.2	1.6	100 (at 79)				

[a] Cement used in groups 4 to 7, inclusive, was ground from clinker A; all other cements were ground from clinker D.
[b] Specimens were 2-inch mortar cubes (1 part cement to 2.75 parts graded Ottawa sand); all specimens were cured in water at 70° F. until tested.
[c] Values are average for six specimens. Specimens were tapped lightly with hammer before weighing; 100 per cent loss in weight indicates when specimens broke completely.

As in the case of the tensile tests, the compressive strength results are also undoubtedly influenced by cement fineness, water ratio, and quantity of carbon. The greater strength increases shown in the compression tests, compared with the tensile tests, are ascribed chiefly to the smaller water differences used in preparing the compression specimen mortars. The substantial increases in compressive strength for the cements containing carbon are due, in the main, to the increased fineness of the cement, although there is evidence that the carbon also has a beneficial effect.

Results of other investigations have shown that the addition of colloidal carbon to Portland cement and sulphur cement compositions definitely increases the strength of these products. It is claimed that colloidal carbon shows this strengthening effect in all compositions containing an aggregate body.

Resistance to Sulphate.

Two-inch mortar cubes were prepared with experimental cements ground from clinker D; mortar proportions were 1 part cement to 2·75 parts graded Ottawa sand. These specimens were submerged in a solution of 2 per cent. sodium sulphate and examined daily for signs of deterioration. Loss in weight was determined after four months. The results are as follows:

Group No.	Properties of Cements		Per cent. loss in weight of Mortars* after 4 months
	Per cent. Carbon by weight	Specific surface, sq. cm. per gram	
1	0	1,427	59
2	0·16	1,521	60
3	0·64	1,767	56
4	2·56	1,897	54
5	5·12	1,851	67

* Figures are averages for six specimens.

The results of these tests reveal that, except possibly for the cements containing 5·12 per cent. of colloidal carbon, the cements containing carbon are fully as resistant to sulphate as control cements.

Resistance to Freezing and Thawing.

A " fast " method of conducting freezing and thawing tests on mortar cubes was employed. In the freezing treatment the specimens were partly immersed in water in a shallow pan; the pan was then placed inside a cork-lined box, covered, and surrounded with solid carbon dioxide. The treatment lasted for two hours, readings on check specimens showing that the temperature inside the specimens reached 32 deg. F. in one hour and a minimum of 5 deg. F. in $1\frac{3}{4}$ hours. This was followed by a one-hour thawing treatment, which consisted of immersion of the specimens in water at 70 deg. F. Readings on check specimens showed that the temperature inside the specimens reached 60 deg. F. in the thawing treatment. The specimens were left in the thawing tank over nights and week ends. The specimens were not handled except when removed for the loss in weight tests. The results of these tests are summarised in *Table* III.

The results lead to the conclusion that cements containing colloidal carbon, particularly in the lower percentages, had a resistance at least equal to the control in freezing and thawing tests. The behaviour of groups 11 and 12 was particularly favourable. The results in *Table* III also show that the resistance of mortars to freezing and thawing is improved when the curing time is lengthened. The effect of cement fineness and water-cement ratio on resistance to freezing and thawing are not pronounced, although the tendency appears to be for the finer cements to have decreased resistance when accompanied by increased water-cement ratios.

TABLE IV.—EFFICIENCY OF GRINDING DUE TO COLLOIDAL CARBON AS A GRINDING AID AT CONSTANT FINENESS.

	—% Passing 325-Mesh Sieve at Grinding— Time of:							——Interpolated Values——	
% Carbon	35 min.	55 min.	60 min.	65 min.	70 min.	75 min.	85 min.	Grinding time for 85% through 325 mesh, min.	% decrease in grinding time
0	56.4	72.2	75.5	79.7	81.5	82.8	85.7	82.6	Control
0.02	57.5	71.8	75.4	78.8	80.6	82.0	85.2	84.4	0
0.04	58.3	74.3	76.8	80.7	83.3	85.0	88.3	75.0	9.2
0.08	55.7	75.3	80.4	82.6	86.3	..	..	68.2	17.5
0.16	61.7	80.6	85.2	86.5	89.3	..	..	59.8	27.6
0.32	60.3	83.2	85.3	89.4	91.3	..	..	59.3	28.2
0.64	61.4	83.6	88.0	92.1	94.1	..	..	56.6	31.5
1.28	64.5	85.3	90.2	93.8	96.6	..	..	54.7	33.8
2.56	58.3	83.6	88.1	90.2	94.3	..	..	56.6	31.5
5.12	56.9	80.3	82.6	88.6	..	..	..	62.0	25.0

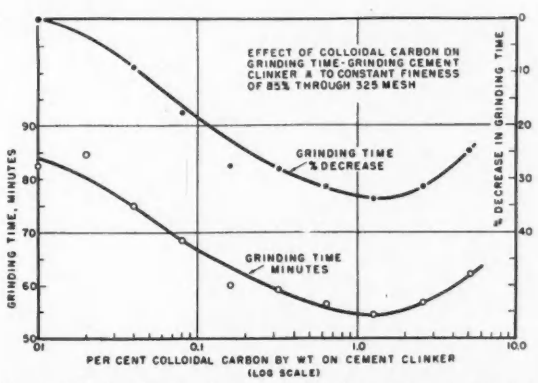

Fig. 3.—Effect of Colloidal Carbon as an Aid in Reducing Grinding Time.

Grinding Time.

A series of grinding experiments was made to determine the effect of colloidal carbon as an aid in reducing the grinding time required to give a cement of definite fineness. Samples of cement were removed from the mill at definite intervals for sieve analysis, and the results were used to determine by interpolation the exact time necessary to give a cement of constant fineness—85 per cent. through a 325-mesh sieve. The experimental and interpolated results are given in *Table* IV. The results bring out the fact that the use of colloidal carbon as a grinding aid effects a striking decrease in the grinding time. The results plotted in *Fig.* 3

show that a maximum decrease of 34 per cent. results with the addition of 1·3 per cent. of carbon and a decrease of 25 per cent. with only 0·2 per cent. In terms of saving power, increased output, and other economies, these figures seem to be of practical significance.

It has been suggested that these high percentage decreases may be due partly to the lack of maximum grinding efficiency, as discussed earlier in the paper, and thus give ball coatings at lower finenesses and magnify the effect of the carbon. That such is not the case is indicated by unpublished results of other investigators, which confirm the percentage values shown in this paper for several proportions of carbon. The contention that the grinding procedure employed in these tests gives accurate comparative results, although it fails to afford maximum effects, seems to be confirmed.

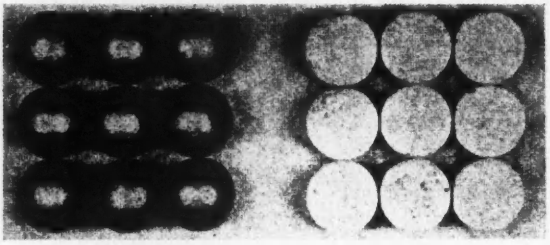

Fig. 4.—Cleaning Effect of Colloidal Carbon on Mill Balls.

It was observed that additions of carbon as low as 0·08 per cent. effectively prevented ball-and-mill coatings. This cleaning effect is demonstrated in *Fig.* 4. The left-hand group of balls was taken from a cement grind containing 0·08 per cent. colloidal carbon and the right-hand group was taken from a control. The shiny metallic surfaces of the left-hand group are clearly illustrated, whereas the right-hand group of balls have heavy coatings of cement. It was also noted that dry cement containing colloidal carbon exhibited improved dry flow properties over the control cement. Improved flow results in better screening behaviour of the material, and facilitates pumping and storage.

Summary.

Colloidal carbon is an effective aid in increasing the fineness of cement ground from Portland cement clinker. This fineness increase, as determined by specific surface measurements, was 30 per cent. with 0·32 per cent. of carbon and reached a maximum of 50 per cent. with 1·28 per cent. of carbon.

Colloidal carbon is an effective aid in reducing the grinding time of clinker. A decrease in grinding time of 28·2 per cent. was given with a proportion of 0·32 per cent. of colloidal carbon ; a maximum decrease of 33·8 per cent. resulted from a proportion of 1·28 per cent.

The cements prepared with the use of carbon as a grinding aid gave slightly higher normal consistency values and somewhat decreased setting time values.

These results were traced primarily to the increased fineness of the cement.

The cements made by the use of colloidal carbon had somewhat higher tensile strengths and markedly higher compression strengths. These increases were probably caused in the main by the increased fineness of the cement, although there was evidence that the carbon also contributed.

The finer cements resulting from the use of carbon showed a resistance to freezing and thawing treatment equal to the control cements containing no carbon.

Colloidal carbon was found to be an effective cleaning agent in the mill with percentages as low as 0·08 per cent. of the clinker.

British Standard Specification for High-Alumina Cement.

A STANDARD specification for high-alumina cement has been issued by the British Standards Institution (price 2s. net). The document prescribes tests for fineness, chemical composition, strength, setting time, and soundness.

Fineness.—The test for fineness is as follows. 100 g. (or say 4 oz.) of cement shall be continuously sifted for a period of 15 minutes on a B.S. sieve No. 170, when the residue by weight, shall not exceed 8 per cent. The sieves shall be prepared from wire cloth complying with the requirements of Table I of B.S. 410—1931, Test Sieves. The sieving surface shall be not less than 50 sq. in. and the depth of the sieves shall be not less than 2¾ in. measured from the surface of the wire cloth.

Chemical Composition.—The total alumina content shall be not less than 32 per cent. by weight of the whole. The ratio of the percentage by weight of alumina (Al_2O_3) to the percentage by weight of lime (CaO) shall be not less than 0·85 nor more than 1·3.

Compressive Strength.—The compressive strength of cement and sand shall be ascertained from cubes having a length of side of 2·78 in.* (the area of face equals 50 sq. cm.).

The material for each cube shall comprise: cement, 190 g.; sand, 570 g.; water, 76 g. Immediately after the mixing, the mortar shall be placed in the hopper of the cube mould in one portion and shall be compacted by a vibrator described in an Appendix of the specification. The mould shall be vibrated for two minutes at full speed and shall not be finished by trowel or by hand. The temperature of the water and of the test room shall be from 58 deg. F. to 64 deg. F. The cubes shall be kept at this temperature in an atmosphere of at least 90 per cent. relative humidity for 24 hours when they shall be removed from the moulds and submerged in water, and left there until taken out for breaking.

Three cubes shall be tested at 24 and 72 hours and the compressive strength shall be the average of the three cubes. The load shall be steadily and uniformly applied at a rate of 5,000 lb. per sq. in. per minute. The compressive strength of

* When so desired, 3 in. cubes may be used for the test in which case the quantities shall be: cement, 240 g.; sand, 720 g.; water, 96 g.

the cubes shall be as follows: 24 hours, not less than 6,000 lb. per sq. in.; 72 hours, an increase on the compressive strength at 24 hours of not less than 7,000 lb. per sq. in.

Setting Time.—The initial and final setting times of the cement shall be determined by means of the Vicat apparatus. A test block shall be made as follows: Neat cement shall be gauged with 22 per cent. by weight of water. The time of gauging shall be not less than three minutes or more than five minutes. The temperature of the water and of the test room shall be from 58 deg. F. to 64 deg. F. The test block shall be kept in an atmosphere of at least 90 per cent. relative humidity and away from draughts. The initial set shall be not less than two hours nor more than six hours. The final set shall be not more than two hours after the initial set.

Soundness.—The cement, when tested for soundness by the Le Chatelier method, shall not show a greater expansion than 1 mm.

British Standard Tests for Laboratory Porcelain.

THE British Standards Institution has issued a British Standard for tests for laboratory porcelain. The tests include: appearance, shape, weight, porosity of body and imperfections in glaze (dye test), resistance to heat and sudden change of temperature, constancy of weight and resistance of glaze to high temperature and to acid and alkali. Some of the tests are based on those adopted by the Glass Research Committee of the Institute of Chemistry and published in 1920. The test of the resistance to heating and cooling is new, it being an accelerated test that offers the manufacturer a control of the quality of standard and experimental material. Copies of the Standard may be obtained from the Institution, price 2s. 3d. by post.

Ball-Mill Grinding.*

Tetrahedrons and Spherical Balls Compared.—An operator furnished 1,000 lb. of tetrahedrons for comparison with spherical balls. The tetrahedrons were all about the same size and the average weight of each was the same as for a 1⅜-in. spherical ball. Four pairs of tests with tetrahedrons and round balls respectively are shown in *Table* 22. The loads weighed 796 lb. each. In the first pair of tests with chert the tetrahedrons were deficient in crushing the coarse particles and they also failed in capacity and efficiency. In the second pair of tests, when dolomite was ground, the type of grinding was about the same, but otherwise the failure of the tetrahedrons was marked. Since the tetrahedrons were of one size, it seemed best to make further tests and compare them with a load of closely-sized balls. Similarly, the ore feed was sized, first plus 10-mesh chert and then 28-mesh to 35-mesh chert. The 1⅜-in. balls used in the sized-ball load were known to be slightly too small for the coarse ore charge and too large for the finer ore charge. The tetrahedrons failed on the plus 10-mesh ore charge, and when the finer ore charge was ground the two media gave the same type of grind; but, as in all the other tests, the tetrahedrons failed in both capacity and efficiency. The keying effects of the tetrahedrons against each other is evidenced by examination of the power records—the tetrahedrons required about 10 per cent. more power than the balls. All in all, they failed by about 15 or 20 per cent. Possibly on account of the large area of the plane surfaces exposed to contact, the tetrahedrons would serve better for grinding excessively fine material.

Ni-hard Balls and Other Balls Compared.—The Carondolet Foundry Co. supplied 1,000 lb. of 2-in. Ni-hard balls for comparison with balls of other composition. Ni-hard balls are said to contain 2·5 to 6 per cent. nickel and 0·5 to 1·5 per cent. chromium. They have a Brinell hardness of 548. The company also furnished a stock of annealed cast-iron balls. They were very soft, having a Brinell hardness of 150, much of the carbon being in a graphitic state. To the stock was added ordinary cast-iron balls for further comparisons. The three batches of balls were used for comparative grinding tests and the results are shown in *Table* 23. The table is in two sections of three tests each. The left section is for chert and the right for dolomite. In the grinding of chert the Ni-hard balls were superior in every way, the order of decreasing effectiveness being Ni-hard, cast iron, and annealed cast iron. In the grinding of the dolomite the Ni-hard balls were superior, but the advantage was not so marked as with the chert.

Examination of the power readings showed that the annealed cast-iron balls required about 10 per cent. less power than the Ni-hard balls. If they had required more power the possible embedding of the ore particles into their surface to increase the nip would have been offered as an explanation; but since the power required by the soft cast-iron balls was less, the presence of graphite must

* Concluded from our issues for April, May, June, July and August, 1940.

TABLE 22.—TETRAHEDRONS AND ROUND BALLS COMPARED.

(Mill, cylindrical, 19 in. by 36 in. Circuit, batch. Speed, 50 per cent. critical. Load, tetrahedrons about same size and about same weight of 1⅜-in. balls. Regular ball load, Davis No. 1; also 1⅜-in. round balls; weight, 796 lb. Volume, 45 per cent. Ore charge, chert and dolomite, weight 50 lb. Consistency, 60 per cent. solids.)

Size, mesh	Unsized chert			Unsized dolomite			Plus 10-mesh chert			−28+35 mesh chert		
	Feed, weight percent	Product, weight percent		Feed, weight percent	Product, weight percent		Feed, weight percent	Product, weight percent		Feed, weight percent	Product, weight percent	
		Tetrahedrons	Regular ball load		Tetrahedrons	Regular ball load		Tetrahedrons	1⅜-inch balls		Tetrahedrons	1⅜-inch balls
8	1.7	1.2	0.3	0.9	0.4	0.2	4.3	2.4	1.3			
10	25.2	13.5	3.7	15.3	5.6	3.6	75.6	37.0	22.0			
14	55.0	28.8	10.4	50.8	19.2	16.2	99.3	63.4	50.1			
20	76.7	40.5	20.7	79.5	34.7	32.5	.7	72.1	62.0			
28	87.2	49.9	33.6	90.2	47.3	46.4		76.7	71.0	0.5	0.3	0.1
35	93.4	58.4	49.4	95.4	57.6	59.1		80.1	77.3	67.4	13.1	14.1
48	96.2	66.0	61.1	97.3	65.8	66.5		83.1	81.2	97.3	42.9	40.6
65	97.9	72.5	71.0	98.2	71.7	72.2		85.7	85.1	99.8	60.9	60.5
100	98.9	78.9	78.2	98.6	77.1	76.9		88.2	88.1	.2	73.4	72.8
150	99.4	83.2	83.5	98.8	80.9	80.8		90.2	90.4		80.1	80.4
200	99.6	86.5	86.9	99.0	84.3	83.8		91.9	91.9		84.6	84.8
−200	.4	13.5	13.1	1.0	15.7	16.2		8.1	8.1		15.4	15.2
Surface tons per hour		21.9	25.2		60.3	70.0		16.2	23.4		23.9	31.4
Surface tons per horsepower-hour		17.6	21.5		47.1	60.0		13.3	19.9		18.7	26.4
Ton per hour		.217	.222		.545	.627		.250	.333		.203	.261
Horsepower		1.238	1.150		1.28	1.17		1.211	1.177		1.273	1.186
Ton per horsepower-hour		.175	.189		.426	.538		.206	.283		.150	.220
Time, minutes		6.9	6.7		2.7	2.4		6.0	4.5		7.4	5.7

explain this. The surface of the annealed cast-iron balls was about 8 per cent. graphite by volume. By acting as a lubricant, the graphite probably caused slipping of the load against the breast of the mill and slipping of the balls among themselves. This would reduce the power requirement. The annealed balls would have been given the same amount of action as the Ni-hard balls if the mill loaded with the annealed balls had been run a little faster. The extra speed would have compensated for the loss in capacity but probably not for the loss in efficiency. With very hard ore the Ni-hard balls showed an advantage that should be given consideration. With hard and moderately hard ores some of the energy of soft balls that should go into crushing goes into deformation of the balls. When the ore is soft, the soft balls are not handicapped so severely.

TABLE 23.—VERY HARD, HARD, AND SOFT BALLS COMPARED.

(Mill, cylindrical, 19 in. by 36 in. Circuit, batch. Speed, 50 per cent. critical. Load, 2-in. balls as noted; weight, 796 lb. Volume, 45 per cent. Ore charge, chert and dolomite, 75 lb. Consistency, 60 per cent. solids.)

Size, mesh	Chert				Dolomite			
	Feed, weight percent	Product, weight percent			Feed, weight, percent	Product, weight percent		
		Ni-hard balls, Brinell hardness 548	Cast-iron balls, Brinell hardness 464	Annealed, cast-iron balls, Brinell hardness 150		Ni-hard balls, Brinell hardness 548	Cast-iron balls, Brinell hardness 464	Annealed, cast-iron balls, Brinell hardness 150
8	1.7				0.9			
10	25.2		0.4	0.4	15.3	0.4	0.8	1.0
14	55.0	0.8	1.7	1.5	50.8	4.2	5.3	7.3
20	76.7	3.9	6.8	4.6	79.5	14.6	17.3	20.3
28	87.2	14.8	18.5	16.1	90.2	30.0	32.1	36.8
35	93.4	32.8	34.9	34.7	95.4	46.1	45.7	52.7
48	96.2	47.1	50.3	49.2	97.3	56.2	56.3	62.0
65	97.9	59.7	62.1	61.8	98.2	64.3	63.9	69.1
100	98.9	69.1	72.2	71.3	98.6	70.4	70.6	74.5
150	99.4	76.0	78.4	77.7	98.8	75.3	75.4	78.6
200	99.6	80.6	82.9	81.9	99.0	79.1	79.7	81.9
−200	4	19.4	17.1	18.1	1.0	20.9	20.3	18.1
Surface tons per hour		26.7	24.4	19.6		73.8	72.9	65.8
Surface tons per horsepower-hour		24.5	22.7	20.2		65.1	65.0	63.2
Ton per hour		167	165	.129		.5	.5	.5
Horsepower		1.091	1.070	972		1.135	1.12	1.042
Ton per horsepower-hour		.153	.154	.133		.441	.446	.480
Time, minutes		13.5	14.0	17.5		4.5	4.5	4.5

Battered Reject Balls and New Spherical Balls Compared.—The authors found an unknown variable when they compared the laboratory work of a new grinding medium with the plant performance of media, some of which may have been in the mill so long that they no longer retained their original shape. Accordingly, reject balls that had assumed the shape of polyhedrons were obtained and compared in the laboratory with new balls of the same weight. The results are shown in *Table* 24. Both the power and the time of grind were greater for the rejects (the efficiency of the rejects was about 11 per cent. less than with the new spherical balls).

Mills of Different Diameter and Length Compared.—Operators may rightly ask how much reliance should be placed on laboratory ball milling when they are using mills so much larger. This question was foremost in the earliest work at Rolla; in fact, in the beginning more attention was given to plant tests than to laboratory tests. The operators had calculated their results in terms of useful grinding and stopped their calculations at 65-mesh because they did not wish to grind finer. Their power was in terms of gross horsepower.

At the various concentrators included in the examination the ores were markedly similar and the particle size of the feeds was about the same. Eventually the companies gave each mill a rating in capacity in terms of surface tons per hour and in efficiency in terms of surface tons per horsepower-hour. When a mill, regardless of its size, was found to have a low efficiency it was given special attention. The examination generally showed that it was making too

TABLE 24.—BATTERED REJECT BALLS AND ROUND BALLS COMPARED.

(Mill, cylindrical, 24 in. by 24 in. Circuit, batch. Speed, 60 per cent. critical. Load, balls, 1⅜ in. Weight, 518 lb. Volume, 27 per cent. (Unit volume of rejects weighs 7 per cent. more than round balls.) Ore charge, dolomite B. Consistency, 70 per cent. solids.)

Size, mesh	Feed, weight percent	Product, weight percent	
		Reject balls	1¾-inch round balls
8	0.2		
10	4.2	0.1	0.2
14	19.3	.4	.7
20	42.2	1.2	1.9
28	61.7	4.6	5.5
35	76.1	14.0	14.7
48	85.6	29.0	29.1
65	90.8	43.0	42.7
100	94.3	55.5	55.5
150	96.1	63.9	64.1
200	97.1	71.2	71.3
−200	2.9	28.8	28.7
Surface tons per hour		91.3	97.7
Surface tons per horsepower-hour		60.5	68.2
Ton per hour		.500	.536
Horsepower		1.51	1.43
Ton per horsepower-hour		.331	.374
Time, minutes		4.5	4.2

much of the minus 65-mesh size in its discharge. If an increase in new feed was not desirable to correct the malperformance, the speed of the mill was reduced to conserve power. This reduction in speed increased the circulating load and increased the selective grinding. In one instance a group of mills was allowed to continue to run at top speed and extra feed was obtained by laying off a superfluous mill. Tests were made concurrently in the laboratory with duplicate feeds, pulp consistency, and presumably duplicate ball loads. The indications were that the laboratory mill was a little superior to the plant mills. However, several indeterminable factors beclouded the tests, such as the size of ball, the exact amounts, and their condition as to shape.

After the laboratory investigation had gone farther and it seemed that the subject was understood well enough for correct interpretations, the tests were

resumed. *Table* 25 contains some of the results. The first half of the table shows a comparison of two laboratory mills that are dissimilar in diameter and length. They were run at the same speed. The results are almost identical. The tests, being of the batch type, were timed so that the amount of work on a unit weight was the same in each mill. The conclusion was reached that a long laboratory mill of small diameter performed the same as a shorter mill with a larger diameter. Parenthetically, this pair of tests illustrates the principle that when two dissimilar mills are loaded and charged in proportion to their volumes the grind in the 24-in. by 24-in. mill (larger diameter) required only 6·75 minutes, whereas the 19-in. by 36-in. mill (smaller diameter) took 8·5 minutes. The explanation lies in the difference in the exponents applied to the diameters for volume and power respectively—the exponent for volume is 2 and for power (capacity) it is 2·5.

TABLE 25.—MILLS OF DIFFERENT DIAMETERS AND LENGTHS.

Size, mesh	Feed, weight percent	Batch grind, chert, 60 percent speed, 60 percent solids		Feed, weight percent	Dolomite, 80 percent speed, 77 percent solids	
		19- by 36-in. mill	24- by 24-in. mill		6- by 4-ft. mill	19- by 36-in. mill
8	1.7	0.1	0.1	4.4	0.6	.03
10	25.2	1.8	2.0	24.6	3.8	2.1
14	55.0	7.0	6.9	44.6	10.2	7.3
20	76.7	18.4	17.0	61.3	19.6	17.0
28	87.2	33.4	31.9	73.8	31.2	29.9
35	93.4	50.3	47.2	82.4	43.1	42.6
48	96.2	62.1	60.3	87.1	53.2	52.4
65	97.9	71.5	70.0	89.5	60.4	59.3
100	98.9	78.4	78.2	94.0	68.8	67.3
150	99.4	83.4	83.2	97.3	75.5	73.6
200	99.6	86.7	86.7	98.7	80.6	78.8
−200	.4	13.3	13.3	1.3	19.4	21.2
Surface tons per hour		29.8	41.4		3,530.0	105.7
Surface tons per horsepower-hour		21.8	22.5		52.7	56.9
Ton per hour		.262	.355		28.0	.79
Horsepower		1.36	1.84		67.0	1.86
Ton per horsepower-hour		.192	.193		.419	.425
Time, minutes		8.5	6.75			4.75
Ball load, pounds		796	846		15,000	890
Ore, pounds		75	80			125

The last half of *Table* 25 shows a comparison of one of a group of 6-ft. by 4-ft. mills with a laboratory mill. In the concentrator the rate of feed was determined and the feed and discharge sampled. While sampling the feed a good quantity was laid aside for laboratory tests. When the laboratory tests were made a close parallel of the grinding results was indicated; the two grinds were almost identical in type. However, some explanation is required. In the first calculations, the net power assigned to the large mill was that of a companion mill taken about two years earlier and immediately after it had been dumped and reloaded with a fresh stock of balls. Finally, a power determination was made on the mill from which the samples had been taken, and it was found to be about 8 per cent. higher than expected. The nature of the ball load was

suspected because it had not been renovated for many months. Many battered balls were present. It was this condition that prompted the test shown in *Table* 24 in which the battered balls were shown to take about 6 per cent. more power than new balls. Taking these things into consideration, it seems safe to expect laboratory mills to duplicate the work of mills of commercial size.

The comparison of the 6-ft. by 4-ft. (in reality, 68-in. by 50-in.) mill with the 19-in. by 36-in. mill gives an opportunity to investigate the accuracy of a simple formula for relative powers. Here the exponent 2·5 will be applied to the diameters, and since the lengths are so nearly the same the power will be taken also as a function of the length. The proportion used to solve for the net power required by the larger mill is

$$19^{2.5} \times 36 : 68^{2.5} \times 50 :: 1{\cdot}86 : X = 63{\cdot}0.$$

The value 63 horsepower, obtained by the proportion lacks about 6 per cent. of checking the value, 67 horsepower, given in *Table* 25. All of these power values are net. The failure to obtain a closer check might be due to a fault in the amount of ore charge selected in the laboratory run. How a small difference in ore charge affects the power may be illustrated by referring to the 80 per cent. speed with dolomite in *Table* 13. There it will be seen that when the mill had a 125-lb. charge the power was 1·75, and when the charge was 100 lb. the power was 1·85. Thus the difference between 100 lb. and 125 lb. of ore in the mill makes a difference in power of about 6 per cent., this being the disparity in the calculation and illustrating that the use of formulae for forecasting power requires full appreciation of the influence of small changes in set and induced variables. These tests led to the belief that if each one of a heterogeneous mixture of mills, large or small, is run under conditions analogous to the others, and if each applies a unit of work to a unit of ore, the effect (comminution) will be the same—that is, the same relation between cause and effect will maintain.

Conclusions from Experimental Evidence on Important Points in Fine Grinding

(1) When identical pipes were stuffed with a variety of substances to simulate rods of different densities, and the mode of operation and the loadings were otherwise alike, the power to run the mill with the respective pipe loads varied as the weight of pipes plus ore plus water.

(2) Pipes stuffed with heavy material gave moderately better selective grinding of chert than did the light pipes; hence, density as well as diameter should be considered. The calculated efficiencies at all densities and speeds were about the same. The work of regular rods of the same diameter as the pipes was superior by about 35 per cent.

(3) A change in particle size effects a change in power. The power dropped 8 per cent. in grinding from one-half on 14-mesh to the same amount on 48-mesh. By using a charge with a much coarser particle size and not continuing the run too long the test could have been devised so that the power range would have been reversed.

(4) When the speed was not too high in batch grinding, a thick pulp was

desirable for capacity, but a thin pulp was better for efficiency. In open-circuit grinding, a pulp thinner than 43 per cent. solids was not satisfactory. In continuous grinding the indications were that the pulp consistency in the mill is the same as in the effluent.

(5) The range of satisfactory speeds for the rod mill was more limited than for the ball mill. High speeds were not efficient, whereas the ball-mill efficiencies did not vary much between 30 and 80 per cent. of the critical. Large discharge openings in the rod mill were always desirable.

(6) Wet rod milling showed the best efficiency and capacity with only 25 lb. of ore in the mill; 39 lb. were required to fill the interstices.

(7) Batch grinding was like open-circuit grinding when the amounts of media, ore, and water in the mill were the same. The types of grind, capacities, efficiencies, and powers were the same.

(8) Rods did more grinding than an equal volume of balls, but more power was required.

(9) Rods of extremely small diameter gave more selective grinding than large balls. The rods, being 35 in. long, were heavier than the balls. Undoubtedly weight was a more important factor than the diameter of the medium in the grinding of coarse particles. Angle of nip does not explain the findings.

(10) In wet-batch ball milling with ore charges from 200 lb. to 35 lb. (about 75 lb. of ore was required to fill the interstices of the balls at rest) and speeds from 30 to 80 per cent. critical, the slow speed gave the same type of grinding as high speed. Heavy ore charges yielded a little more selective grinding of the coarse particles than light charges. Best capacities were obtained with light charges, and slightly better efficiencies were obtained with heavy ore charges.

(11) Some of the characteristics of dry-batch ball milling were unlike those of wet grinding. In the dry work, efficiency as well as capacity were best with the light ore charge. Power decreased with decrease in the amount of ore in the mill; in wet grinding it increased with a decrease in the amount of ore in the mill. In dry grinding high speed was more efficient than low speed.

(12) In comparing wet and dry grinding the tests were paired so that all the set variables were the same, except pulp consistency (wet or dry). With an intermediate weight of ore charge, selective grinding was of the same degree; with a heavy ore charge, wet grinding was more selective, and with the light ore charge, dry grinding was more selective.

(13) In comparing wet and dry open-circuit ball milling, wet grinding gave 39 per cent. more capacity and 26 per cent. more efficiency.

(14) A small ball volume was not satisfactory in the overflow type of dry mill because too much ore built up in the mill. When building up of the ore was prevented by simulating the low pulp-level mill, the small ball volume did good work.

(15) With 60 per cent. solids, pebbles of the same size as balls did about the same type of work as balls when dolomite was ground, but they failed in selective

grinding of chert. Pebbles gave about 35 per cent. of the capacity and 81 per cent. of the efficiency shown by the balls.

(16) For hard and medium-hard ores, tetrahedrons were unsatisfactory for coarse grinding.

(17) Very hard balls (Ni-hard) were better than ordinary balls; this was particularly so when the ore was very hard.

(18) The efficiency of battered reject balls was about 11 per cent. less than that of new spherical balls.

(19) A ball mill as small as 19 in. by 36 in. duplicated the work of a plant-size mill. The tests led to the belief that if each of a variety of mills, large or small, is run under the same conditions, and if each applies a unit of work to a unit of ore, the effect (comminution), as indicated by the products, will be the same—that is, the same relation between cause and effect will maintain.

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